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Filtering fens: Mechanisms explaining phosphorus-limited hotspots of biodiversity in wetlands adjacent to heavily fertilized areas

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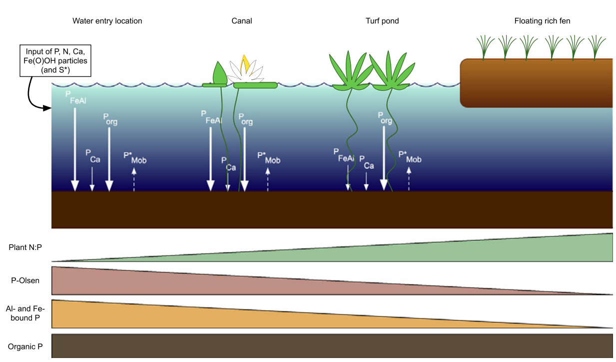
HIGHLIGHTS

- The periphery of large wetlands acts as an efficient P-filter.
- Filtering services are crucial to preserve P-limited, biodiverse fens in eutrophic areas.
- Precipitation of Fe-phosphates and biological sequestration are important filtering mechanisms.

GRAPHICAL ABSTRACT



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ABSTRACT

The conservation of biodiverse wetland vegetation, including that of rich fens, has a high priority at a global scale. Although P-eutrophication may strongly decrease biodiversity in rich fens, some well-developed habitats do still survive in highly fertilized regions due to nutrient filtering services of large wetlands. The occurrence of such nutrient gradients is well-known, but the biogeochemical mechanisms that determine these patterns are often unclear. We therefore analyzed chemical speciation and binding of relevant nutrients and minerals in surface waters, soils and plants along such gradients in the large Ramsar nature reserve Weerribben-Wieden in the Netherlands.

P-availability was lowest in relatively isolated floating rich fens, where plant N:P ratios indicated P-limitation. P-limitation can persist here despite high P-concentrations in surface waters near the peripheral entry locations, because only a small part of the P-input reaches the more isolated waters and fens. This pattern in P-availability appears to be primarily due to precipitation of Fe-phosphates, which mainly occurs close to entry locations as indicated by decreasing concentrations of Fe- and Al-bound P in the sub-aquatic sediments along this gradient. A further decrease of P-availability is caused by biological sequestration, which occurs throughout the wetland as indicated by equal concentrations of organic P in all sub-aquatic sediments.

Our results clearly show that the periphery of large wetlands does indeed act as an efficient P-filter, sustaining the necessary P-limitation in more isolated parts. However, this filtering function does harm the ecological quality of the peripheral parts of the reserve. The filtering mechanisms, such as precipitation of Fe-phosphates and

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biological uptake of P, are crucial for the conservation and restoration of biodiverse rich fens in wetlands that receive eutrophic water from their surroundings. This seems to implicate that biodiverse wetland vegetation requires larger areas, as long as eutrophication has not been seriously tackled.

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1. Introduction

Many minerotrophic freshwater wetlands show large heterogeneity at the landscape scale, as they consist of a mosaic of open water, aquatic vegetation, semi-aquatic vegetation, rich fen, poor fen and swamp forest, as a result of the ongoing process of succession and terrestrialization. In the first half of the 20th century, biodiverse floating rich fens with *Scorpidium scorpioides* (Hedw.) Limpr. developed in mesotrophic waters on root mats of helophytes, such as *Typha angustifolia* (L.) and *Phragmites australis* (Cav.) Steud (e.g. van Wirdum, 1995). However, due to eutrophication, sulfide toxicity and/or ammonium toxicity in these waters, new formation of rich fens has hardly occurred during the past decades in countries such as the Netherlands (van Wirdum, 1979; Roelofs, 1991; Smolders et al., 2003). The sustainability of the present rich fen remnants strongly depends on sufficient input of base-rich water to avoid fast succession towards a more acidic but less biodiverse, *Sphagnum*-dominated poor fen vegetation (Sjörs, 1950). Species-rich rich fens also require phosphorus (P) poor conditions (Kooijman and Paulissen, 2006) to prevent accelerated succession and outcompetition of rare species by graminoids (Kooijman, 1993; Cusell et al., 2013a).

Most European wetlands, however, receive water from areas with intensive agricultural land use, leading to a high supply of N and P by surface water and/or groundwater (e.g. Koerselman et al., 1990). This may have resulted in the accumulation of P in sub-aquatic sediments during the past decades (Lijklema, 1980; Lamers et al., accepted for publication). The subsequent mobilization of accumulated P may lead to additional eutrophication (Patrick and Khalid, 1974), especially under sulfate (SO_4) rich conditions. Under anaerobic conditions, the reduction of iron (Fe) and SO_4 leads to mobilization of Fe-bound orthophosphate (Caraco et al., 1989), and high SO_4-concentrations may stimulate organic matter decomposition and P-mineralization (Drever, 1997). Despite this large-scale eutrophication, remnants of sensitive and biodiverse habitat types, such as rich fens, still exist in some of the wetlands involved. This is probably caused by the spatial differentiation of N- and P-concentrations in the surface water and sub-aquatic sediments, with decreasing concentrations from water entry locations and main canals towards more isolated sites (van Wirdum, 1979; Lijklema, 1980; Craft and Richardson, 1993).

So far, little attention has been paid to the mechanisms that determine this gradient in larger wetlands. In this study, it is hypothesized that not all incoming P will be transported by surface water flows to the most isolated parts of wetlands, because part of the P-input will precipitate rather close to the entry locations. Furthermore, P-uptake by vascular plants, algae and micro-organisms, which occurs throughout wetlands, will presumably lead to a further decrease of P-concentrations in the surface water, especially during the growing season. These P-fractions accumulate in sub-aquatic sediments, where they may be stored permanently or become available again by desorption, dissolution and mineralization, posing a secondary risk of P-eutrophication.

In order to identify the role of these biogeochemical mechanisms, we conducted a landscape-scale study in the Dutch National Park 'Weerribben-Wieden', a large wetland surrounded by heavily fertilized agricultural lands, which still comprises biodiverse rich fen vegetation with *S. scorpioides*. Our main aim was to determine which mechanisms explain the change in nutrient availability, especially for P, in waters and soils along a gradient from water entry points in the periphery to more isolated vegetation sensitive to eutrophication. These insights are not only important to understand the functioning of wetlands that receive high anthropogenic nutrient inputs, which is the case for many European and American wetlands that lie in the vicinity of agricultural areas, but also to understand nutrient biogeochemistry in more pristine wetlands.

2. Material and methods

2.1. Site description

National Park Weerribben-Wieden is a Ramsar site in the central part of the Netherlands (between 52°48′ N–5°53′ E and 52°38′ N–6°08′ E; Fig. 1), characterized by a maritime temperate climate with a mean annual precipitation of about 800 mm (KNMI, 2014). There is a precipitation surplus in winter, while large parts of the summer (April–August) are generally characterized by an evapotranspiration surplus. The atmospheric N-deposition is about 18 kgN ha^{-1} $year^{-1}$ (1300 mol ha^{-1} $year^{-1}$; RIVM, 2012), which is lower than the national average.

Until the 17th century, this area was part of a large wetland that was bordered by an inland sea (the Zuyderzee) in the west and moraine upland in the east (Haans and Hamming, 1962). This wetland changed dramatically between the 17th and 20th century due to peat excavation, which was carried out below the groundwater level, and the subsequent terrestrialization of abandoned turf ponds (van Wirdum, 1995). During the 20th century, most of the original wetland area and parts of the Zuyderzee were reclaimed and drained to develop agricultural polders (van Wirdum, 1990). The remaining wetland of about 9500 ha was conserved to serve as a regional water storage basin. In this basin, substantial terrestrialization occurred during the first half of the 20th century, and a mosaic of open canals, lakes and turf ponds with aquatic and semi-aquatic vegetation developed, including poor fen, rich fen and swamp forest.

The remaining wetland has an average surface level of 0.3–0.6 m below mean sea level (BMSL), and surface water levels are maintained at 0.73–0.83 m BMSL throughout the year. The surrounding polders are lower with surface levels of 1.0–2.5 m BMSL (van Wirdum, 1990). These polders, which are drained by about 30 pumping stations to maintain various lower water levels of 1.5–3.0 m BMSL, discharge excessive water volumes into the higher lying wetland. Water levels in the wetland reserve itself are regulated by one main pumping station, which removes water during wet periods and sporadically pumps water in during pronounced dry periods.

The annual water balance for National Park Weerribben-Wieden, which is based on the activities of pumping stations and data about precipitation and evapotranspiration between 2000 and 2012, shows that the water input of the present wetland consists for 37% of rain water, for 15% of water from the adjacent upland and for 48% of water from lower lying agricultural polders (Cusell et al., 2013b). The discharge of polder water is about 50% smaller in summer than in winter. Hence, the composition of water in the remaining wetland is largely determined by the land use of the surrounding polders and the season. During the second half of the 20th century, when arable lands and meadows received excessive amounts of fertilizer and manure, these inputs of polder water led to severely increased N- and P-inputs into the National Park (van Wirdum, 1979).

The specific amounts and distribution of these inputs differ, however, substantially throughout the year (van Wirdum, 1990). Previously, a 1D–2D model for surface water flows (SOBEK; Deltares systems, Delft, the Netherlands & ARCADIS, Apeldoorn, the Netherlands) was used to determine water flow patterns in National Park Weerribben-Wieden throughout the year (Cusell et al., 2013b). This model was based on

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